Combustion of Shelled Corn in a Small-Scale Fluidized Bed

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ABSTRACT

Fluidized bed combustion is an attractive method of extracting energy from a wide variety of fuels. This study analyzed operating parameters for shelled corn combustion in a 15.2 cm diameter, 44-kW atmospheric fluidized bed burner. Variables studied include sand particle size distribution, fuel particle size, moisture, air/fuel ratio, and bed depth. Increasing moisture from 16% to 22% reduced bottom bed temperature slightly, without significantly changing the rest of the bed profile temperatures. Increasing bed depth from 0.58 m to 0.71 m reduced the freeboard temperature while increasing heat energy in the sand bed. A system based reaction rate constant was developed and mass loss profiles and residence times of the various particle sizes were determined. Solving an energy balance for the system, k values (reaction rates) gave 0.3 min-1 for whole shelled corn and 0.4 min-1 or greater for particles sizes smaller than 5.7 mm. Combustion characteristics, chemical and physical properties, and fluidization behavior of whole and cracked shelled corn are presented. In particular, the activation energy for ground corn was found to be 68,630 J/mol using ASTM E 1641-04. Combustion efficiencies ranged from 93-99% for particles smaller than 5.7 mm and approximately 85% for the whole shelled corn. It should be noted that feed rates were the fixed variable, so excess air was lower for the whole shelled corn. More studies to control the air-fuel ratio are needed. Design strategies for the fluidized bed combustor including bed material and size, available air flow, and air/fuel ratios are discussed.

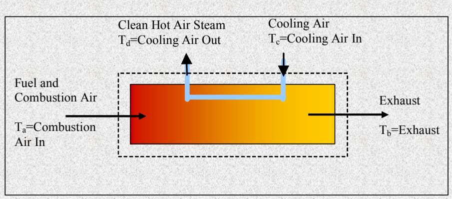
INTRODUCTION

Conventional methods of energy production are insufficient due to the uncertainty surrounding the availability of fossil fuels, their associated expense, and tightening environmental legislation. Shelled corn is desirable because of its sustainability, low cost, high energy value, availability, and because it does not require additional processing steps.

It is hypothesized that whole shelled corn can be combusted efficiently in the OARDC-FBC. Based on the proposed research, design parameters and operating efficiencies of the bed could be optimized for specific fuel conditions, such as size and moisture, or predetermined set points could be created based on the fuel used, thus making commercialization of small FBC units more practical for residential or small business applications.

1. Establish Measurement Repeatability
2. Determine System Fluidization Characteristics and Factors
3. Examine Combustion Kinetics and Properties of Fuel
4. Study the Effects of Fuel and FBC Parameters

The OARDC-AFBC, Combustion Research Lab, Department of Food, Agricultural, and Biological Engineering, OARDC, Wooster, OH.



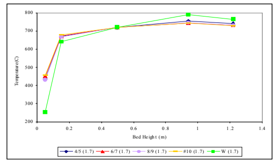
Bed Depth	Moisture	Particle Size						Feed Rate
		Whole	#10	4/5	6/7	8/9	10/12	
22"	16%	$\blacksquare_1$	$\blacksquare_4$	$\blacksquare_3$	$\blacksquare_3$	$\blacksquare_3$		1.4
		$\blacksquare_1$	$\blacksquare_4$	$\blacksquare_3$	$\blacksquare_3$	$\blacksquare_3$	$\blacksquare_1$	1.7
	22%				$\blacksquare_3$			
28"					$\blacksquare_3$			
	16%	$\blacksquare_1$	$\blacksquare_1$				$\blacksquare_1$	

Test plan indicating combination of parameters tested. Particle size refers to Tyler standard sieve size used to screen corn. Feed rate was a dial setting on the feeder.

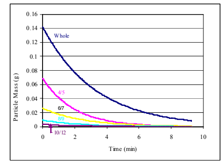
CONCLUSIONS

- Whole Shelled Corn Exhibited Higher Peak Temperatures and Lower Bottom Bed Temperatures
- Particles smaller than whole demonstrated nearly identical results
- Deeper Bed Depths Reduced Peak Temperatures and Increased Bottom Bed Temperatures, Most Noticeably with Whole Shelled Corn
- Higher Moisture Content of the Fuel Lowered Bottom Bed Temperatures
- Combustion Efficiencies ranged from 93-99% for Particles other than Whole

RESULTS AND DISCUSSION



Bed profile of various particle sizes at the same feed rate setting

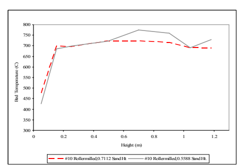


Predicted particle mass loss over time according to Equation 1.

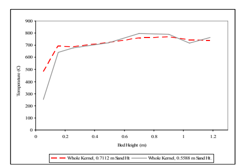
The differences in peak bed temperatures between whole and cracked particles are possibly caused by the integrity of the seed coat or larger mass of the particle and longer residence time. This could be due to the particles taking a longer time to ignite upon entry into the bottom of the bed. The fuel particle is behaving endothermically and absorbing heat from the bottom of the bed resulting in a lower bottom temperature. By the time the whole shelled corn ignites and combusts, it is already higher in the bed. Based on predicted particle mass loss, it is evident that whole kernels require much longer time to achieve similar mass loss to cracked particles.

The value for heat energy generated can be used to determine the velocity constant, k, which indicates the rate at which the fuel is consumed. An estimate of the rate constant was made based on the measurements from the actual performance of the AFBC using the equation below. where θ is the time variable. For this calculation, dQ_{gen} is the total heat generated during a given test, dθ is the length of the test, and m_{fuel} is the total mass of dry fuel consumed.

$$\frac{dQ_{gen}}{d\theta} = k m_{fuel} HHV \qquad \text{Equation 1}$$

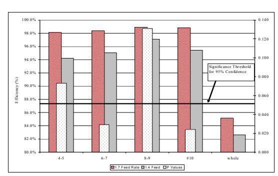


Bed temperature vs. bed height for #10 particle distribution



Bed temperature vs. bed height for whole particle distribution

The higher peak temperatures occurring at higher bed heights of whole corn were reduced by adding sand height to the bed. This supports the theory that by exposing the particles to the sand bed for a longer period of time more of the burning occurs before the particles escape into the freeboard. Experiments with higher bed heights were limited based on the physical design of this FBC.



Average efficiencies shown with p-value results from t-test

Combustion efficiency, η_c, measurements are calculated from gas samples as well as gravimetric ash measurements and $\dot{m}_{C/CO}$ is the mass rate of carbon burning to CO, $\Delta H_{C/CO_2}$ is the heating value of carbon to CO_2, $\Delta H_{C/CO}$ is the heating value of carbon to CO, $\dot{m}_{c/ash}$ is the mass flow of carbon rejected to ash, $\dot{m}_{fuel}$ is the mass flow of the fuel, and HHV is the high heating value of the fuel.

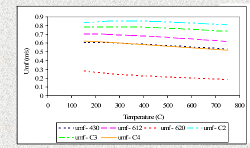
$$\eta_c = 1 - \frac{\dot{m}_{C/CO}(\Delta H_{C/CO_2} - \Delta H_{C/CO}) + \dot{m}_{c/ash}\Delta H_{C/CO_2}}{\dot{m}_{fuel} HHV}$$

MATERIALS AND METHODS

Fluidizing Media

$$\frac{1.75}{\alpha_{mf}^3\varphi_s}\left(\frac{d_p u_{mf}\rho_g}{\mu}\right)^2 + \frac{150(1-\alpha_{mf})}{\alpha_{mf}^3\varphi_s^2}\left(\frac{d_p u_{mf}\rho_g}{\mu}\right) = \frac{d_p^3\rho_g(\rho_s-\rho_g)g}{\mu^2}$$

The above equation for minimum fluidizing velocity, u_{mf}, dictates sand selection used for the fluidizing media. Based on air properties at operating temperatures and using predetermined data, the desired sand should have a u_{mf} of about 0.4 m/s, which corresponds to custom sand mixture, C4.



Bed temperature effect on calculated minimum fluidization velocity for sand mixtures: #430, #612, #620, C2, C3, and C4.

US Sieve Number	Mean Sieve Opening (mm)	Custom Sand Mixture	
		x_i	$(x/d_p)_i$
6	4.06	7 %	0.017
8	2.87	40 %	0.139
10	2.19	21 %	0.095
12	1.84	25 %	0.135
16	1.435	7 %	0.488
$\Sigma(x/d_p)_i$			0.437
$1/\Sigma(x/d_p)_i$			2.287

Mean diameter of fluidizing media with a distribution of sizes.

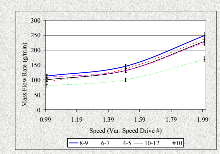
Fuel Selection

Picture showing (a) whole shelled corn, (b) #9 rollermilled, (c) #10 rollermilled, (d) 4/5, (e) 6/7, (f) 8/9, and (g) 10/12.

Name of Tested Sample	Diameter (mm)
Whole shelled corn	mostly 5.98
4/5	4.38 – 5.21
6/7	3.10 – 3.68
8/9	2.19 – 2.61
10/12	1.55 – 1.84

Sample name of shelled corn particles indicating sieve size and approximate size range of particle diameter.

Air/Fuel Mixture



Feed rate variation due to particle sizes: #10, 4/5, 6/7, 8/9. and 10/12

Wt. %	Dry	Dry ash free	As received	
C	41.7	42.3	37.9	Measured
H	6.4	6.5	5.8	Measured
O	49.2	49.9	44.8	Calculated
N	1.1	1.12	1	Measured
S	0.1	0.1	0.09	Measured
Cl	0.05	0.051	0.045	Measured
Total	99.9	99.9	100	

Ultimate analysis of shelled corn, providing percent C, H, O, N, S, and Cl (Smeenk, Brown, and Eckels,1999)

Reaction at 0% Excess Air

$$C_{3.475}H_{6.4}O_{3.075}N_{0.079}S_{0.003} + 3.619\,O_2 + 13.614\,N_2 + 1.258\,H_2O + ash =$$
$$3.458\,CO_2 + 0.017\,CO + 4.458\,H_2O + 0.031\,O_2 + 13.614\,N_2 + 0.079\,NO_2 + 0.003\,SO_2$$

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Anderson, R.J., Keener, H.M., & Henry, J.E. (1984). U.S. Patent No. 4,671,251. Filed September 24, 1984.
Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Progress Energy Combus Sci*, 30, 219-230.
Fan, L.S., & Zhu, C. (1998). Principles of Gas-Solid Flows. New York: Cambridge University Press.
Geldart, D. (1973). Types of gas fluidization. Powder Tech., 7, 285.
Glassman, I. (1996). Combustion. (3rd Ed.). San Diego, CA: Academic Press, Inc.
Goodger, E.M. (1977). *Combustion Calculations: Theory, worked examples, and problems.* New York: Macmillan Press Ltd.
Keener, H.M. (1989, March-April). Design of a 0.3 MW atmospheric fluidized bed combustor with a concentric air heat exchanger. *Transactions of the ASAE*, 32 (2), 403-407.
Kunii, D., & Levenspiel, O. (1991). Fluidization engineering, (2nd edition). Boston: Butterworth-Heinemann.
Oka, Simeon N. (2004). Fluidized Bed Combustion. New York: Marcel Dekker, Inc.
Smeenk, J., Brown, R.C., & Eckels, D. (1999, 29 August-2 September). Determination of vapor phase alkali content during biomass gasification. *Proceedings of the Fourth Biomass Conference of the Americas*, Volume 2. (pp. 961-967). Oakland, CA.